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RESEARCH ARTICLE

What the Jeweller's Hand Tells the Jeweller's Brain: Tool Use, Creativity and Embodied Cognition

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Abstract The notion that human activity can be characterised in terms of dynamic systems is a well-established alternative to motor schema approaches. Key to a dynamic systems approach is the idea that a system seeks to achieve stable states in the face of perturbation. While such an approach can apply to physical activity, it can be challenging to accept that dynamic systems also describe cognitive activity. In this paper, we argue that creativity, which could be construed as a 'cognitive' activity *par excellence*, arises from the dynamic systems involved in jewellery making. Knowing whether an action has been completed to a 'good' standard is a significant issue in considering acts in creative disciplines. When making a piece of jewellery, there a several criteria which can define 'good'. These are not only the aesthetics of the finished piece but also the impact of earlier actions on subsequent ones. This suggests that the manner in which an action is coordinated is influenced by the criteria by which the product is judged. We see these criteria as indicating states for the system, e.g. in terms of a space of 'good' outcomes and a complementary space of 'bad' outcomes. The skill of the craftworker is to navigate this space of available states in such a way as to minimise risk, effort and other costs and maximise benefit and quality of the outcome. In terms of postphenomonology, this paper explores Ihde's human-technology relations and relates these to the concepts developed here.

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1 Introduction

This paper is about the ways in which people, specifically jewellers, create objects. Jewellery making is an area of human activity in which cognition, creativity and physical performance meet. We will argue that such behaviour can provide fertile ground for considering cognition and creativity. In order to develop the argument, we will apply the frame of radical embodied cognitive science (RECS) to data collected in laboratory and field settings (where the sources of these data range from interviews to data collected using motion capture and sensors fitted to tools) to explore tool use and creativity. We feel, as Hutchins (1995) emphasised, that the primary way to appreciate embodied activity is through the study of skilled practitioners in their places of work. Our concern is with the ways in which technological artefacts (and, in this context, we mean the tools, the equipment, the materials and the workplace) play a role in shaping jeweller's activity and, specifically, in shaping creativity. Of particular relevance to our discussion are Ihde's (1990, 2009) notions of embodiment, hermeneutic, alterity and background relations between humans and technology. We will draw links between these relations and our observations to show how technology mediates human activity through a process of mutual co-construction and argue that 'creativity' arises from the dynamic interplay between jewellers and their technology.

Jewellers' engagement with their creative practice has received surprisingly limited attention in the literature (Rajili et al. 2015). One can draw parallels between jewellery and other artisanal practices, such as pottery, glassmaking and furniture making, and realise that the processes of 'designing' and 'making' are often difficult to disentangle (Malafouris 2008; Ingold 2010). Mäkinen (2005) found that jewellers include 'making' in their account of design practice. In jewellery making, it is necessary to combine knowledge of metallurgy and gemstones, with craft skills and an ability to create aesthetic designs. The craft skills themselves involve a wide range of techniques from cutting and setting stones to piercing and cutting metal, to casting metal and construction of finished pieces. These craft skills encompass the jewellers' know-how and are typically not separated from their design skills. From this, one could suggest that 'creativity' is simply a consequence of skilled performance of physical activity, but this feels unsatisfactory in terms of a concept of creativity as an ability to create something novel (as opposed to the well-practised ability to repeat previous designs).

2 Creativity and Action in Jewellery Making

Ingold (2010) traces back to Aristotle, the common conceptualisation of craftwork or artistic practice as a matter of bringing form (*morphe*) to matter (*hyle*). This 'hylomorphic' concept presupposes that form is imposed on matter, often as the result of an idea that is conceived prior to the act of making. Ingold (2010) challenges the idea that 'creativity' is solely concerned with imagining the form in one's mind prior to the physical act of making. In this paper, we will develop a similar argument, albeit taking a different route to the conclusion. Before developing the argument, it is useful to consider a contemporary account of creativity which has an (perhaps unintended) emphasis on hylomorphism. Boden (1996) offers two types of creativity which she terms 'improbabilist' and 'impossibilist'. In the former, a novel combination familiar ideas represents something that is new to the individual (which Boden also calls psychological or P-creativity), and the latter involves the mapping, exploring and transforming of conceptual spaces to create new ideas which could not have generated previously (which Boden call historical or H-creativity). This suggests that a characteristic of creative activity lies in making unfamiliar combinations of familiar ideas, through exploring and transforming conceptual spaces. For Boden, creativity is a cognitive act that is performed in the head. Her theory motivates a research agenda in artificial intelligence (AI) in which she explores ways in which computers could be capable of creativity in this manner. However, this separation of 'creation-in-the-head' and a physical behaviour that is merely the acting out of this 'cognition' seems to miss an essential aspect of the jeweller's work. Boden (1996) and related accounts of creativity imply that the creative act must plan, predict and script the actions which need to be performed. However, it is not obvious that it what happens in jewellery making. In their account of studio jewellers, Wuytens and Willems (2009), following the lead of Schön (1983), suggest that work involves three processes in a chain of *reflective moments*, which focus on 'design parameter', 'design cluster' and 'backtracking'.

'Design parameter reflection' involves exploring, reflecting upon and elaborating the constraints that are implied by a given design brief. In some sense, design parameter reflection could be seen as an example of Ihde's (1990) hermeneutic relation, in that the jeweller is reading the potential design. In this case, such a reading involves both the given material (in what state it currently exists) and the possible states that it could achieve, given the constraints under which it is being worked. There are several means by which constraints can be explored. One might be to create a sketch of the intended design. When it is used, the sketch is a means of thinking through, or explaining, the technical problems of making an item (Baber and Saini 1995). Pereira and Tschimmel (2012), in their account of designing a series of pieces suggested by Saint Saëns 'Carnival of the Animals', note that sketching is used to create 'ideation drawings' used to explore concepts. 'By drawing, the designer expands the problem space of the project task, to the extent of including and even discovering, new aspects, which he / she considers relevant, as much as through a subsequent interpretation of the graphic representations.' (p. 104). In other words, the jeweller's sketch is not a fully dimensioned engineering drawing that the jeweller replicates in whatever material is being used. In this way, the sketch does not serve as a template for the final product or a plan for manufacture so much as a physical form of problem solving.

The sketch externalises a *potential* design, both in terms of making the design visible so that it can provide 'feedback' to the jeweller (or to the jeweller's client) but also in terms of a physical action of moving pencil across paper to reveal unexpected, unanticipated and new opportunities of form (Schön 1983). The hermeneutic relations of reading the form that the piece could take is, thus, partly a cognitive act of responding to the visual appearance of the sketch (or the material) and partly a physical exploration of the ways in which materials can be modified. In other words, in exploring alternative designs, the jeweller could be said to be instantiating 'events', which Chemero (2000) defines in terms of the layout of affordances in the animal-environment system. From this point of view, sketching is a means by which the jeweller's relation to the environment can be reflected upon and, as such, becomes a way of exploring 'conceptual spaces' (Boden 1996) through physical as much as cognitive activity. In large part, the sketch provides an opportunity to consider the constraints that could affect making. However, sketching is also an act in itself and the sketch rarely becomes the formal blueprint for the object to be made. If the role of the sketch is to provide a way of exploring potential design options, then one can see how this could be replaced, or complemented, by the physical manipulation of the materials being worked. Accounts of jewellery practice emphasise the experimental nature of the construction work itself. Pereira and Tschimmel (2012) note that 'The creation of jewellery involves processes, which are often very experimental and intuitive, encompassing both the creative process and production techniques.' [p. 97]. This is similar to the suggestion that physical activity on objects can support problem solving. For example, in their study of Tetris playing, Kirsh and Maglio (1994) distinguish between the pragmatic acts involved in moving the pieces to form patterns, and the epistemic actions involved in moving the pieces in an exploratory manner to see whether patterns are available. In a study of the 'wolves and chicken' problem, Guthrie et al. (2015) show that the ability to interact with physical objects led to a reduction in 'illegal' moves and a reduction in decision latency (suggesting that participants were more efficient when they could manipulate physical objects than when they verbalised the approach to the problem). Steffensen et al. (2015), in a fine-grained analysis of strategy in solving the 17 Animals problem, demonstrate how rearranging the physical artefacts in the task led to serendipitous recognition of the path to a solution. In each of these examples, the interactivity between the person and the materials to hand create opportunities for the recognition of problem solutions. As one of the jewellers interviewed by Rajili et al. (2015) puts it, jewellery design involves '…being very analytic and then go[ing] back to working with your hands then look[ing] at what you've been doing and analysing it and taking it further. …it allows you to kind of digest your thought and it's there in the back of your head all time anyway and so it kind of leads you anyway towards what you would like to express.' This quotation could be read in terms of Boden's (1996) notion of a cognitive act ('in the back of your head all the time') which informs and guides creativity. But we claim that the quotation is also contrary to Boden's understanding of creativity as a cognitive act followed by construction acts. Rather, there is a constant interplay between what is happening 'in the head' and the what is being done with materials.

'Design cluster reflection' involves grouping aspects of constraints together to consider how dependencies can be tackled. In her account of creative practice, Malinin (2016) proposes that creative cognition is embodied, embedded and enacted. In part this reflects the observation that skilled practitioners do not distinguish between the tool as an external artefact and their hands but, rather, feel the tool as part of themselves (Baber 2003; Sennett 2008). This illustrates Ihde's (1990) embodiment relations in that jewellers regard the tools, materials, decorative objects or other features of their settings as things to think with. This form of 'epistemic action' (Kirsh and Maglio 1994) could involve manipulating a stone to catch the light or experimenting with the arrangement of pieces prior to assembly which, in turn, suggest particular solutions to the mounting or construction problem.

Wuytens and Willems' (2009) notions of 'constraint' and 'backtracking' relate to the properties of the materials being worked and the visual appearance of the finished design. This calls to mind Deleuze and Guaterri's (2004) focus on materials and forces (which a theoretical stance Ingold (2010) builds upon). The notion of constraint can be related to Boden's (1996) notion of conceptual space, in that the 'creative' solution to the problem of producing a piece of jewellery involves appreciating opportunities offered within a space of constraints. In Pereira and Tschimmel's (2012) terms, 'A creative perception of the situation depends mainly on the designers' previous experience and from [the] ability to handle [a] wealth of experience in a flexible and imaginative way, applying creative thinking operations, such as associative thinking, thinking in analogies, visual reasoning and perception with all of the senses.' (p. 98).

3 Chopping Logs and Making Jewellery: Outcome Criteria and Creativity

In Ihde's (2012) account of wood chopping, the wood is the 'focal core' [Ihde 2012, p. 30] to which attention is directed, with the tool (axe), the praxis associated with the tool and the self as a wielder of the tool all being secondary foci of attention. Anyone who has wielded an axe knows that none but the most expert can guarantee that the spot they pick will be exactly the spot that the axe hits, and even if this is the same spot, it will not guarantee that the wood will split. If a log is split into sizes which can feed a wood burner or which can be put into a log basket, then this tends to be sufficient. There remains a troublesome misreading of this description, which is that the tool-user has an intention which is brought forth by their use of the tool. This is similar to Boden's notion that 'creativity' begins as an intention, in the head, and is then realised through action. For Malafouris (2013), this problematic arises because of the assumptions that can be implicitly made about 'intention'. In his account of flint knapping (which echoes much of the discussion in the next section, albeit from a different perspective and using different terminology), Malafouris (2013) suggests that 'The decisions about where to place the next blow and how much force to use are not taken by the knapper in isolation; they are not even processed internally. The flaking intention is constituted, at least partially, by the stone itself. Information about the stone is not internally represented and processed by the brain to form the representational content of the knapper's intentional stance. Instead, the stone, like the knapper's body, is an integral and complimentary part of the intention to knap.' [p. 173]. From this, one can see why Malafouris (2013) argues so strongly, in his Material Engagement Theory, that one does not simply act upon artefacts but rather that one actively engages and interacts with them. For Ihde's (1990) postphenomonology, this active engagement involves the mutual constitution and co-construction of intent between human and technology in which human relations with their world becomes transformed through the technologies they use.

For Malafouris (2008) assuming that the human is an agent who acts upon inert objects presents a misconception of the timescale at which actions take place. In part, this stems from an over-reliance on local notions of cause and effect. If one extends the timescale, he argues, then one can see an interplay of acting and responding that shifts between human and object. In its suggestion that we need to rethink the way in which timing of actions is considered, this supports the focus on time-series analysis that is at the root of the dynamic systems approaches inherent in RECS. Agency, as a central tenet of Material Engagement Theory, emerges through the interactivity of person and material. An ‘agent’, in this respect, can be anything which shapes or influences the behaviour of something else. Thus, in flint knapping, the stone being worked, the hammer stone and the hand of the knapper could all take on the role of ‘agent’ at different times in the ongoing interaction.

In both log splitting and flint knapping, we can recognise the end-state of an action when it occurs (as desirable or not) but it is not so easy to provide accurate prediction of when that state will occur or what form the resulting product will be in all situations. Rather, the outcome relies on a combination of the kinetic energy and angle of incidence of the impact, together with the properties of the material. For Ingold (2006), this combination of factors characterises the skilled tool user; the force, amplitude, speed and torque of the moving tool; and the posture and movements of the tool-user change from stroke to stroke. For us, this is a defining feature of the dynamic systems modelling of human activity which is central to RECS. Consequently, there is a mediation between the material’s state and the ‘system’ that changes the material’s state. Bateson’s (1972) account of tree-felling involves the system of ‘tree-eyes-brain-muscles-axe-stroke-tree’ (p. 317). This idea of a ‘system’ (comprising tool, material, person etc.) foregrounds the theme of this paper, which is to ask how actions that are performed can be managed as part of a complex, co-adaptive and creative system. If tool-using actions can be described in terms of system dynamics, then there remains an open question concerning the ‘cognition’ at play here. If one assumes a separation of the physical act of using a tool and the cognitive acts involved in creativity, then there seems to be an impasse. A way around this is to turn to a conceptualisation of cognition which is sense-saturated (Cowley and Vallée-Tourangeau 2013), embodied (Chemero 2009) and materially engaged (Malafouris 2013). In this manner, cognition becomes a matter of managing the coordinated accumulation of sensory experience, together with the performance of appropriate actions in response to these experiences and the constraints provided by a given situation for a given system. Embodiment relations, therefore, become not only a way of acting but also a way of knowing; with experience and practice, the skilled jeweller is able to anticipate changes in material and to respond to these through changes in the use of the tools and equipment.

For the jeweller, the finished product has to meet certain culturally defined, aesthetic standards. Not only does this mean that the final product is evaluated in terms of quality, but also that the consequences of each stage of the production process could be evaluated in terms of its potential impact on the finished piece; sloppiness in the initial stages creates the need for reworking or, at least, corrective action, later on. In terms of hermeneutic relations, the reading of the piece must occur over several different levels and timescales: the jeweller reads the piece as it develops from instant to instant, making adjustments in action to maintain the development; the jeweller refines the idea of the ‘finished’ piece as it develops; the jeweller develops the physical appearance of the piece (its size, shape, weight, look etc.) in terms of the aesthetics that would be most appropriate for the potential wearer of the piece. In jewellery making, one could say that the hermeneutics are applied on past (pieces like this one that had been made previously), present (how this piece looks at this precise moment) and future (how the piece is likely to turn out). One jeweller we spoke to said that they like to ensure that all features were finished to a high standard, even if the part becomes hidden by other pieces or is on the back of the piece, not because it can be seen but because the jeweller will know it is there. Valuing these 'hidden' features makes less sense from a view that assumes the form is imagined and then created (unless one either assumes that the imagined form has a totality of the visible and hidden aspects), but makes far more sense if one assumes that creativity reflects the dynamic interplay between craftworker and material. It also makes sense if these hermeneutic relations are mediated by embodiment relations (Ihde 1990). If a dynamic systems' account of activity is to challenge the hylomorphic tradition that Ingold (2010) identified or to speak against the (representational) schema-based approaches that Chemero (2009) challenges, then it also needs to be able to speak as clearly of actions and outcomes in the future as it does of actions and outcomes in the here and now.

4 Dexterity, Dynamics and Tool Use

Working in the tradition of Bernstein (1967), Bril and her colleagues have been exploring the question of dexterity in the use of tools. Much of this work has concentrated on the ways in which stone is worked, either in terms of flint knapping (Bril et al. 2010, 2012; Nonaka et al. 2010; Parry et al. 2015; Rein et al. 2013) or in terms of stone-bead making (Biryukova and Bril 2008; Roux et al. 1995). Across a series of studies, Bril demonstrates that differences between expert and novice practitioners can be explained in terms of the ability to respond to contextual demands. To paraphrase Bernstein, dexterity is not simply a matter of more coordinated bodily movement but an enhanced responsiveness to the surrounding conditions. Such responsiveness can be measured in terms of behaviour, e.g. in terms of precision, flexibility, regularity, adaptability, smoothness, swiftness and optimisation. Following the lead of Bernstein, Bril considers behaviour as arising from the recognition, and satisfaction, of task-specific mechanical constraints. These mechanical constraints could include the force to apply, the velocity or distance to move the tool to produce such force and the angle of incidence for impacts between tool and material. The constraints define the functional parameters which need to be managed in order to achieve successful performance in the task, and Bril's work shows how experts and novices differ in their ability to work to these functional parameters. Given the range of actions that people could perform (as indicated in the well-known degrees of freedom problem[1]), Bril follows Bernstein in proposing a hierarchical control model. In this approach, functional parameters can be achieved through regulatory parameters through which the person

[1] Bernstein (1967) famously proposed that all human movement involved the need to solve the degrees of freedom, or motor equivalence, problem. The human arm (from shoulder to hand) has joints at the shoulder, elbow and wrist. Each of these joints can move in more than one direction, and each direction of movement can be thought of as a degree of freedom. This means that any movement of the arm could involve seven degrees of freedom (three about the shoulder—yaw, pitch and roll; one about the elbow—pitch; three about the wrist—yaw, pitch and roll). The suggestion that there are seven degrees of freedom assumes that one is only interested in the motion of joints. However, there are further degrees of freedom arising from the agonist-antagonist activity of muscles connected to the joints, and the manner in which muscle control is coordinated. From this, any movement could involve more than one solution.

controls specific movement parameters. For instance, experts (flint knappers and stone bead makers) seek to hold the functional parameter (kinetic energy) constant when they use different types of hammer or material, while novices vary kinetic energy with different types of hammer. Recently, this concept was applied to the comparison of jewellers performing simple sawing tasks, showing the experience relates to the grip force applied to the handle and to the velocity of the saw blade during cutting (Baber et al. 2015).

As Bernstein noted, it is important to incorporate feedback into the closed loop control of motion, in terms of the interaction between person and environment. This feedback can be seen as a means of managing the dynamics of the human-tool-environment system. Rather than considering movement as the enactment of a program or schema, an alternative view is to consider the control parameters which need to be optimised. Thus, an optimal control model would seek to determine the 'cost function' which is being minimised while allowing the goal of the movement to be achieved. Bernstein spoke of coordinative structures in which combinations of muscle activation become associated with specific movement in levels of synergy. As activity is performed, the interactions between elements in the coordinative structure vary, depending on the way in which it is being controlled and the way in which it is affected by the environment around it. This frames the point made by Ingold (2010), cited earlier, that there is a moment-by-moment, stroke-by-stroke variation in the tool wielding movements of the skilled craftworker. In this way, one can consider activity in terms of softly assembled systems in which activity is contextually constrained and embodied and in which repetitive actions share a 'family resemblance' but exhibit variability.

> Local interactions among embodied processes on different timescales weave the intrinsic fluctuations of the component processes into a coherent fabric of flux, despite inherent tendencies of the different processes to vary at their own different rates (on their own timescales). Competitions among local rates of change strike a precise balance with globally emerging cooperative activity. In the precise balance of (or near) the critical state, they produce a long-range correlated, aperiodic pattern of change or flux in behaviour… The aperiodic flux is called 1/f noise… (Kloos and Van Orden 2009, p. 259).

1/f noise can be applied across different cognitive tasks to indicate a 'softly assembled' system focussing on interaction-dominant dynamics (component dynamics alter interactions) rather than component-dominant dynamics (behaviour arises from components, demarcated and assigned specific functions). Richardson and Chemero (2014) show how *1/f* scaling has been observed across a wide range of human activities. In part, this reflects the motor component of the activity being studied and the ability of people to adapt to situational demands as embodied systems. For example, Dotov et al. (2010) demonstrate that hand-mouse coordination in a simple video game exhibits *1/f* scaling during normal operation but not when the task is disrupted. This indicates that, during normal operation, hand-mouse control can be described as an interaction-dominant system. Applying this concept to jewellers, *1/f* scaling can distinguish skill levels in the use of jewellery saws (Baber and Starke 2015). Furthermore, there are activities which would be considered cognitive, i.e. possessing less dependence on motor control, which such scaling. For example, Stephen et al. (2009) demonstrate the making inferences correspond to the fractal dynamics of eye movements when solving problems. As Richardson and Chemero (2014) note, 'This indicates that even leaps of insight do not occur in the brain alone – the eye movements are part of the interaction dominant system that realizes the cognitive act.' (p. 45). Thus, there is compelling evidence that human activity exhibits long-term stability (or repeated patterns of variability) that indicate the existence of interaction-dominant systems. While the patterns that *1/f* scaling provides a means of analysing the temporal dynamics of activity, they do not provide clues as to how actions might be coordinated or controlled. To consider this, we turn to an approach which considers the control mechanisms of interaction-dominant systems.

5 Uncontrolled Manifold Hypothesis

One of the studies that Bernstein conducted involved an early form of kinematic analysis to explore variability in a blacksmith's movements. When a repetitive action is performed, such as hammering or sawing, the action is highly stereotyped but each instance differs from the others. In other words, these actions exhibit variability across repetitions. Bernstein noticed that the variability in the position of the hammer's head was smaller than variability in each of the joints in the arm holding the hammer as it was swung to hit the target. Rather than specifying the movement for each joint, coordination appears to involve the management of a 'unit' (which he terms a coordinative structure) which exhibits kinematic redundancy. Assume that you move your hand towards an object that you intend to touch. The degrees of freedom (about shoulder, elbow and wrist) mean that there are many ways in which this action can be performed, e.g. imagine approaching the object from its left or its right side and you can appreciate differences in possible movement. If one considers the movement around each joint, then there are times when each joint's movement appears to be towards the object and other times when the movement might be orthogonal to the object. From this, one can assume that there is a set of movements which can be described as controlled, i.e. towards the object, and a set which are not. Scholz and Schöner (1999) propose that the ratio between motion in the 'towards the object' space and the orthogonal space can be used to indicate the degree of control within a 'unit'. The uncontrolled manifold hypothesis (UCM) assumes that movement control involves the fixing of some parameters with others being left free. This neatly follows Bernstein's concept of coordinative structures and assumes that not all aspects of movement are controlled (thus reducing the degrees of freedom which need to be solved). This reduces the complexity of the control problem and assumes that movements tend to focus control on a few parameters. This echoes Bril's notion of regulatory parameters.

To appreciate how UCM seeks to describe the control of movement, let us assume a movement of the hand reaching towards an object on the table directly in front of you. In this case, movement on a horizontal plane, with single degree of freedom for shoulder, elbow and wrist, can be defined in terms of discrete position in two-dimensional space. At any time, the position on a given joint in space can be defined in terms of *x*, *y* coordinates in terms of a function (*f*) of the angle of the three joints, i.e.

$$(x, y) = f(\theta_1, \theta_2, \theta_3)$$

More specifically, the positions of each link (L) in the reaching system (shoulder, l_1; elbow, l_2 and wrist, l_3) can be defined for *x* and *y* as:

$$x = l_1\cos(\theta_1) + l_2\cos(\theta_2) + l_3\cos(\theta_3)$$
$$y = l_1\sin(\theta_1) + l_2\sin(\theta_2) + l_3\sin(\theta_3)$$

Assume that motion is in line with the target path (||UCM) or perpendicular to that path (⊥UCM). The ratio of ||UCM/⊥UCM indicates whether the movement is 'controlled' (or stabilised). If you sample the movement at defined time intervals, e.g. take the total movement time and divide into ten equal segments, it is possible to plot the ratio of ||UCM to ⊥UCM at each time interval. As the ratio approaches zero, the degree of control is relatively low, and as the ratio increases towards or above 1, then the degree of control is relatively high.

Figure 1 shows the UCM ratio of hand and end of saw for two sawing tasks. The data were averaged from five people performing sawing tasks for around 20 s each, and the data were collected using Motion Capture equipment with markers on shoulder, elbow, wrist, hand and the end of the saw. One task involved sawing vertically into a piece of wood. This is an unusual posture for the participants, who were unfamiliar with this style of sawing. Figure 1 has two pairs of lines (indicating the hand and saw performing the horizontal, H, and vertical, V, movements). The lines on Fig. 1 for V_hand and V_saw show the UCM ratios are above 1 (which indicates a high level of control) and that the line for V_hand tracks that of V_saw, suggesting that the hand and

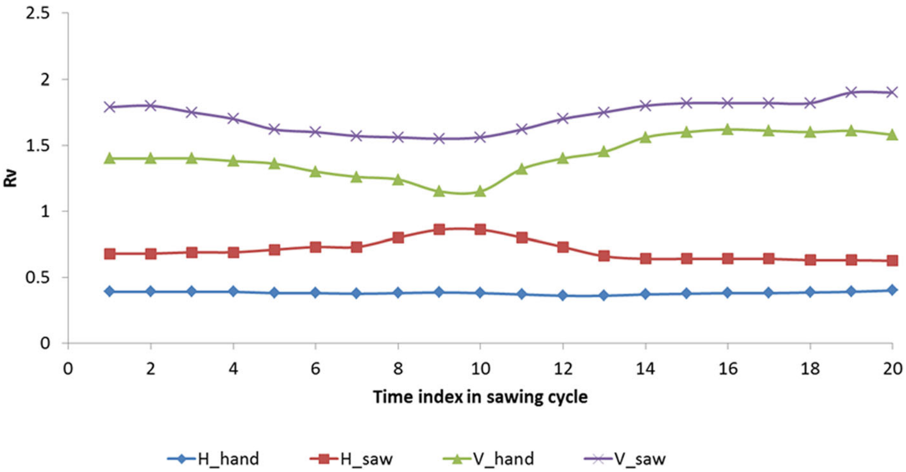

Fig. 1 UCM from pooled data from five participants performing two sawing tasks

saw are forming a combined unit for this task. One might expect this to be the case, if one assumes that a tool is always an extension of the person. However, the line for H_saw is higher than that for H-hand, suggesting that there is more control of the saw than the hand, but there is little alignment between the two ratios. The slight peak in the 'H_saw' line could represent the point at which the saw changed direction, perhaps as a result of a little 'kick' at the end of each forward stroke. There is little difference in the hand ratio, suggesting that the focus of attention was on moving the saw, with the hand (potentially) separate from the saw. One interpretation of this discrepancy (between vertical and horizontal sawing) is that the 'system' that is required to perform a given task will be assembled using the minimum number of components that need to be brought under control, *and that practice with the familiar horizontal task reduces the number of components.*

The point that we are illustrating through the use of *1/f* scaling and UCM is that it is possible to describe human activity using time-series analysis and the mathematics of dynamic systems. These approaches help to bring into focus the ways in which the continual balance between variability and consistency in human activity can be described. Such dynamic systems analyses necessarily emphasise the interplay between the components of the human-tool-material 'system'. In other words, we present this as an illustration of task differences arising from the manner in which soft-assembled systems might function. It also shows how the trade-offs between functional and regulatory parameters that Bril describes become an important feature of skilled performance and suggest that the moment-by-moment adjustment in the control of these parameters (as illustrated by Fig. 1) reflects the shifting emphasis in stroke-by-stroke movement that Ingold (2010) describes and, potentially, the changes in locus of agency that Malafouris (2008, 2013) presents.

6 Temporal Dynamics of Human-Tool-Material Systems

Two metals can be heated in a crucible to produce an alloy that can be poured into a mould. The melting points of the metals (and their transition from solid to molten) can be defined in terms of quantifiable states in this process. The experienced jeweller can look at the metal as it melts and estimate when it is most ready for pouring. Thus, the changes in colour or other indicator of the metals' 'states' could reflect some vocabulary of a particular workshop and these might be more difficult to quantify (than, say, temperature). This could mean that different workshops will develop a different way of explaining and, consequently, training the recognition of such states. In this instance, the 'state' could refer to any condition of the material as it is being worked.

A jeweller might work to avoid undesired states. Examples in jewellery production could include material too hot/cold, material bent/stretched out of true, soldering too messy or joint too weak. The way in which these undesired states are recognised and dealt with (accept and continue with the work, correct or scrap) defines the work practice of a workshop. In terms of creativity, these also provide opportunities for the production process to move along lines that might not originally have been intended, e.g. an 'accident', where a piece is bent out of shape, could create an interesting design that could be worked further.

An agate cabochon (i.e. slice of agate which has been cut with a flat back and domed face) could be mounted in a bezel (which would be flush with setting and would cover the edges of the stone) or a claw (which would show the stone's edge) or wire-wrapped (see Fig. 2).

Production of the cabochon itself can take the form of an ellipse (in which lack of symmetry can be hidden from all but the closest visual inspection in ways that are harder to disguise with circular designs), and this shape will be cut from a piece of stone and then trimmed to a stencil before being polished (depending on the desired finish). Thus, when the jeweller selects an agate cabochon in a bezel setting, there are already a whole set of practices, techniques and design criteria to which this selection commits her. The decision could be influenced by the way that the stone responds to working or by the use of a pre-wrought bezel into which to fit the stone. As the stone is worked so the jeweller might decide to switch from bezel to wire wrapping. The choice of mounting commits the jeweller to a course of action. The performance of the action then creates possible variations, e.g. a claw mount could involve four parts positioned symmetrically around the edge of the stone, but the definition of 'symmetry' in this case could depend on how the stone is oriented. So the jeweller might turn the stone to see how light reflects from it in different orientations prior to creating the claw. In these examples, 'design parameter reflection' is the interplay between the state of the material being worked and jeweller's response to that state. This suggests that jewellers are able to recognise aesthetically pleasing options as they arise without having fully formed mental images (or, indeed, detailed drawing) against which to work. In fact, the originality of pieces of jewellery will come from the jeweller's ability to present the stone in its best possible light rather than simply replicating another design.

A jeweller might arrange the environment in such a way as to support the transition from one part of the production process to the next. This could be deliberate, as in laying out components of a multi-feature design and moving these around until the arrangement looks acceptable, or manipulating the setting for a stone so that the stone does not require cutting. Or it could involve gathering the tools to perform a specific function, or allocating different areas of the workshop to functions. This would ensure that the equipment required is available and that the location of the equipment and the material to be worked on is ready to hand. Keller and Keller (1996) speak of the layout of a blacksmith's forge in terms of a taskonomy, suggesting that the experienced smith could look at the current state of a colleague's forge and has an idea of what is being made. This use of objects in the world can also apply to the creation of jewellery itself.

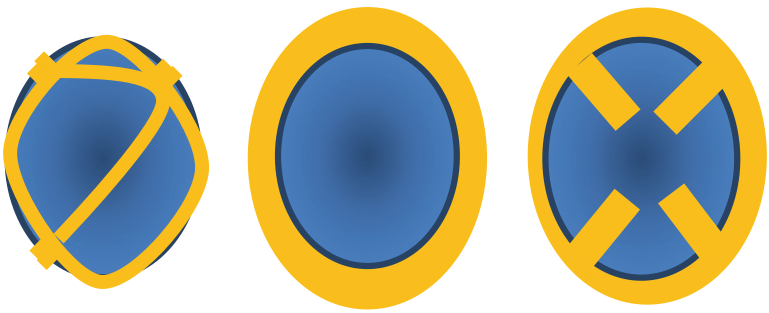

Fig. 2 Types of setting for cabochon (from left: wire-wrapped, bezel/pendant, claw)

A jeweller could use simple concepts to convey a complex design. For example, assume a stone of a given diameter to be fitted into a round brooch. The brooch could have other jewels to offset the central one; these could be arranged along four lines of symmetry (shown as dotted lines in Fig. 3).

Principles of symmetry and balance serve to constrain the choices of placement of stones in this design. Of course, the jeweller might opt to subvert symmetrical patterns but this would still be a decision that is shaped by the lines of symmetry expressed by Fig. 3.

A jeweller might arrange their body in response to the task being performed and in preparation to move to the next task. This postural predisposition is common in sports and involves placing the limbs in position to complete one action and begin the next. In UCM terms, this involves shifting control between body segments. Rosenbaum et al. (2014) demonstrated the ways in which people adopt uncomfortable postures initially because they are seeking comfort in an end-state (turning wine glasses) or in order to exert maximal torque (faucets). Similarly, reach-to-grasp actions are modified by perceived properties of object (Jeannerod 1997; Wing et al. 1997). In these examples, posture is adapted to suit future task demands. The posture we adopt not only 'anticipates' the end of the movement but also defines the regulatory parameters to monitor. This, in turn, constrains the functional parameters which can be managed. Of course, there is likely to be a trade-off here but the initial conditions limit the functional parameters. Initial conditions would be morphological type of grasp, orientation of tool etc. as well as motoric (effort etc.), and each of these can be influenced by the type of tool being used, the experience of the tool user, the material being worked and the effect to be achieved.

A common technique in the production of metal items involves laying a sheet of the metal, say silver, over a form (Fig. 4). The form can be carved into a dome or further carved with shapes and features. As the sheet is hammered against the form, so it begins to take on the shape of the form.

So, one can imagine a sheet of silver laid over a dome and hammered until it forms a bowl. The dimensions of the form and the thickness of the metal set some of the

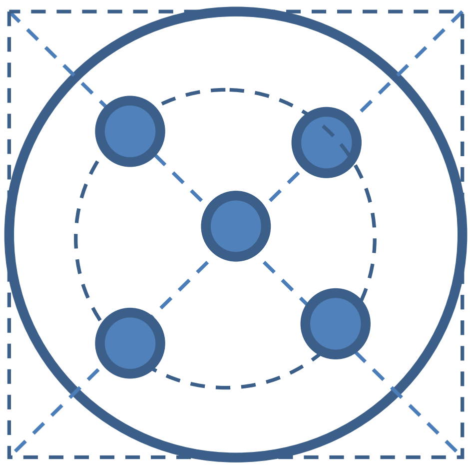

Fig. 3 Placement of stones in a symmetrical pattern

Fig. 4 A metal form (source: http://userblogs.ganoksin.com/primitive/2011/01/17/manufacturing-hammered-sheet/)

constraints of the task. Some silversmiths will mark concentric circles on the sheet to guide their activity. Thus, the process becomes one of defining constraints and working within these. Selecting a specific hammer (with a particular face, a particular weight, a particular handle etc.) commits the smith to a style of hammering, e.g. once the piece has taken on an acceptable form, then a different hammer (a flat-faced mallet made of wood, hide, nylon which will not mark the metal) will be employed for final shaping and finishing.

Each of the hammers in Fig. 5 has a different type of head which results in different impacts on the material being worked and which consequently involves different movements to control the impact forces. UCM suggests that there are efficiency gains to be made from identifying the system elements which are most important in the control of an action. Defining functional and regulatory parameters allows us to postulate which aspects of a system will be controlled. Jewellers' training, guidebooks, web posts etc. are replete with advice which, on the one hand, collates tacit knowledge gained from experience and which, on the other hand, help us to identify constraints that influence their movements and actions.

7 Creativity in Dynamic Systems

Much of the work applying dynamic systems concepts to human behaviour relies on the fact that activity is embodied and involves the performance of physical actions. If one recognises 'creativity' as an essential feature of cognitive activity, then this could

Fig. 5 Examples of jewellers' hammers: (from left) planishing, rawhide, ballpein, chasing, bossing, forging

be potentially precluded from dynamic systems accounts. Our aim in the last part of this paper is to demonstrate how this preclusion is unwarranted and that it is possible to consider creativity in part of the physical behaviour of the jeweller, as well as any other skilled practitioner whose activity is explicable in terms of dynamic system. This relies on four observations.

The first observation builds on the concept of 'reflective practice (Schön 1983; Wuytens and Willems 2009). The 'creative' act is inseparable from the 'physical' act in that they are intertwined and influence each other (Ingold 2010). The skilled craftworker responds not only to the state of the material as it is being worked but also to the possible future states into which it will transform. There is a sense in which the process of transformation is 'mechanised' through the use of tools, forms etc. but at various points in the process, decisions between alternative courses of action remain possible. The navigation of these decision points becomes one hallmark of creativity.

The second observation, which follows from the first, is that creativity is a cyclical response to changing situational cues '… all creation…has the same foundation: gradual steps where a problem leads to a solution that leads to a problem.' (Ashton 2015, p. 59). Consider the simple action of filing an edge on a piece of metal (Fig. 6). After a few strokes, the file is lifted from the piece, filings blown away and the piece visually inspected. The inspection is directed at not only checking whether the edge is smooth but also whether the finish on the metal is acceptable.

The first and second observations relate to, and expand, Ihde's (1990) idea of a hermeneutic relation between humans and technology. The reflective practice of the jeweller and the cyclical response to changing situational cues become an essential mode of acting upon the materials in order to produce a piece. These observations also reflect Ihde's alterity relations (Ihde 1990). One interpretation of alterity relations could be as a way of envisaging the final piece being worn by the client; at some point during its production, the piece ceases to be worked materials and begins to become something that has a life of its own. Jewellers speak of instances in which a piece 'wanted' to be shaped or modified in a certain way, as if instead of jewellers dictating the design, the piece began to reveal itself to them. Precisely how this experience of the piece coming into being has not been captured by the methods we have applied in this paper, but it is a fascinating line for further enquiry.

The third observation is that creativity involves a repertoire of responses and abilities to interpret and respond to cues and constraints. This carries the assumption of means-end problem solving, in that a state in which the system is stable can allow movement to other states. It also sees creativity in an opportunistic manner rather than in terms of

Fig. 6 Filing a disc of copper

specified paths to defined solutions. Expertise becomes a matter of recognising and responding to potential states of the material. Clearly, this reflects Ihde's (1990) embodiment relation, and our aim in this paper has been to highlight that this could be usefully described mathematically (through dynamic systems methods such as *1/f* scaling and uncontrolled manifold hypothesis). We are not arguing that these methods reveal the individual's behaviour (which requires qualitative description and practitioner reflection to elucidate) but that such methods can provide a lens on specific aspects of skilled behaviour. As such skill develops, so it is possible that the relations between technology become backgrounded; not in the sense that these background relations are, like a refrigerator the technology is not part of our activity, but that tools or materials fade into the background of conscious awareness, while the objective of creating a specific effect or finish is foregrounded. As we have argued, jewellery making is a matter of recognising and responding to constraints.

The fourth observation is that the existence of constraints is in no way inimical to creativity. Indeed, any skilled activity depends upon the existence of some constraints (Csikszentmihalyi 1997; Marquc et al. 2011), and human performance generally suffers in the face of too many options. In jewellery making, constraints are imposed by the materials being used, the tools, the design brief, aesthetic considerations, historical considerations and so on. These constraints leave many degrees of freedom uncontrolled and so hardly determine the final product. Yet without them, a jeweller could never get started. Contrast making a ring with turning on a light switch. In the case of the light switch, the possible actions are so constrained that only one outcome is possible. This leaves no room for creativity. This is echoed in recent work on jazz pianists by Walton et al. (2015). They found that pairs of jazz pianists considered their playing to be more creative when they co-improvised along with drone tracks as compared to standard swing tracks. Listeners to recordings of these performances agreed. In both cases, the pianists were constrained by their training, aesthetic considerations, the history of jazz and one another, among other things; however, in the case of the swing track, they were also constrained by a time signature and the chord sequence, not to mention prior recorded improvisations over that chord structure. These additional constraints reduced the players and listeners judgements of the creativity of the performance. The moral here is that some constraints are necessary for creativity, but not so many that few degrees of freedom are left uncontrolled. It would also appear that skill in the use of particular tools for working particular materials solves additional degrees of freedom (through the definition of posture, force and other parameters), allowing the attention of the jeweller to focus on a smaller set. In this respect, knowing how to work materials and knowing the effects of particular approaches to such working practices are inseparable from the capability to create new forms and effects in these materials.

8 Discussion

In this paper, we have presented jewellery making as an example of creative practice and, through this, asked how it is possible that the processional aspects of using tools can result in 'creative' output. The examples provided illustrate how the arrangement of components, the nature of the metal or stones being worked, the practice associated with using specific tools all serve to constrain the conceptual space in which the jeweller operates. Consequently, changes to the materials being worked would create new problems to solve. If the solutions are successful then this leads to the identification of new possibilities and new practices; if the solutions fail, then this would close off these options (at least, until another practitioner offers an alternative approach to solving the problem or a new tool or material becomes available). This echoes the notion of 'craft' that Dormer (1997) offered, as '...knowledge that empowers a maker to take charge of technology.' [p. 140]: for us, 'technology' is that mix of tools, materials, work practice etc. In a sense, this creates the 'presence' of which Noë (2012) speaks. As one becomes more proficient at wielding tools or at working stones and metals, so the range of possible choices expands. '…[I]t is not simply that the craft worker has 'superior' manipulative skills than other people, nor that they are just 'better' at using their hands than other people, but rather that the craft worker has a different view of the world and the artefacts it contains.' [Baber 2003, p. 52]. That is, creativity and creative practice not only change the artefacts that are being worked by also the practitioner (Fry 2012). Critical to this notion is the recognition that there will be decision points at which the path of development of a given design *could* be altered. The action would, one hopes, be under the control of the jeweller but there is ample opportunity for action to arise due to physical forces, e.g. metal being heated too much, metal being hammered too thin, stones cut at the wrong angle or breaking etc. In these cases, the state of the material is as likely to be undesirable or (for the design at least) catastrophic. So, the creative jeweller is an embodied participant in a system of activity in which the interactions between jeweller, materials and tools combine towards the creation of an item of jewellery. From this perspective, the actions of the jeweller appear to be adaptive responses to constraints. These constraints were described in Baber (2003) in terms of different forms of engagement and range from responding to environmental constraints to morphological and motor activity, to perceptual and cognitive response to changes in state and to the cultural practices of each workshop which influence choice of material, processes and designs. This raises the question of when and how the jeweller exercises creativity. We have noted that, while jewellers might spend some time thinking about and sketching design ideas before committing to production, there is often a blurring between design and making. Indeed, the act of making provides opportunities for design. We feel that the practice of jewellery making is much closer to Boden's (1996) view of creativity than might, at first, appear. Indeed, we claim that the role that Boden assigns to conceptual spaces is primarily played by the set of material, aesthetic and historical constraints that enable the creative act. These could be played out through the act of sketching out ideas, or the experimentation and re-arrangement of components prior to making, or through the desire to emphasise a feature of a particular stone in the design. In each case, the 'conceptual space' is realised in the physical space and there is little need to engage in mental simulation when the components are to hand. One might accept that our account could correspond to Boden's (1996) notion of P-creativity, in which 'new' combinations are created for an individual, but that this is still some way from H-creativity, in which entirely new objects are created. Jewellery making takes place under numerous constraints, in terms of the materials used and how they can be worked, in terms of the requirement that the item of jewellery is worn on the body, in terms of the cultural milieu in which items of jeweller are made (what society might expect from jeweller or what a given workshop or manufacturer might claim as its copyrighted or signature designs). These constraints can define the borders of the conceptual space in which creativity occurs. In terms of Ihde's (1990) postphenomonology, managing this space of constraints involves the ability to engage in hermeneutic relations across several levels, and acting in this space involves embodiment relations in which tools, equipment and materials become a part of the physical 'system' (jeweller-technology-material-workplace) which is involved in the production of jewellery pieces. As each piece develops, so there could be points at which they gain their own 'personality' and begin to impose constraints on the developing production process. We offer this as an example of alterity relations (although positioning this in the dynamic process of producing jewellery, possibly as abrupt transitions in this process, is something which requires further development). Finally, as the jeweller becomes immersed in the interplay between tools, equipment and materials, there are instances when any combination of these fades from conscious awareness as attention is given to specific form being made (rather than the specific manner in which this form is made). Thus, our view of creativity is one in which human-technology relations create an interplay between the state of the material and the action of the jeweller. In contrast to the idea that creativity begins with an end in mind, we argue that it involves the discovery of the end. However, this is not to say that new items cannot be imagined, e.g. on the basis of incorporating new or unusual materials into jewellery or in terms of identifying unfamiliar parts of the body on which to place jewellery. If the new items become popular and fashionable, then this design would redefine the culturally acceptable bounds of conceptual space for further development. In terms of combinations of familiar ideas, the jeweller works with a lexicon of design styles which range from notions of symmetry and balance to styles of fixture for stones, to techniques for working materials and to the cultural milieu in which jewellery is designed, made and sold. The balance between the unfamiliar combination and the workable solution becomes as much a matter of physical reality as conceptual aspiration.

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